

# *The Spallation-Neutron-Source Ring Lattice & Analysis*



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# Outline

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- Lattice design philosophy
- Main lattice
  - Evolution of SNS ring lattice
  - Functions and super-periodicity
  - Working point consideration
- Injection
  - Layout; transverse painting
- Extraction
- Correction systems
  - Chromatic sextupole families
  - Other corrections
- Summary

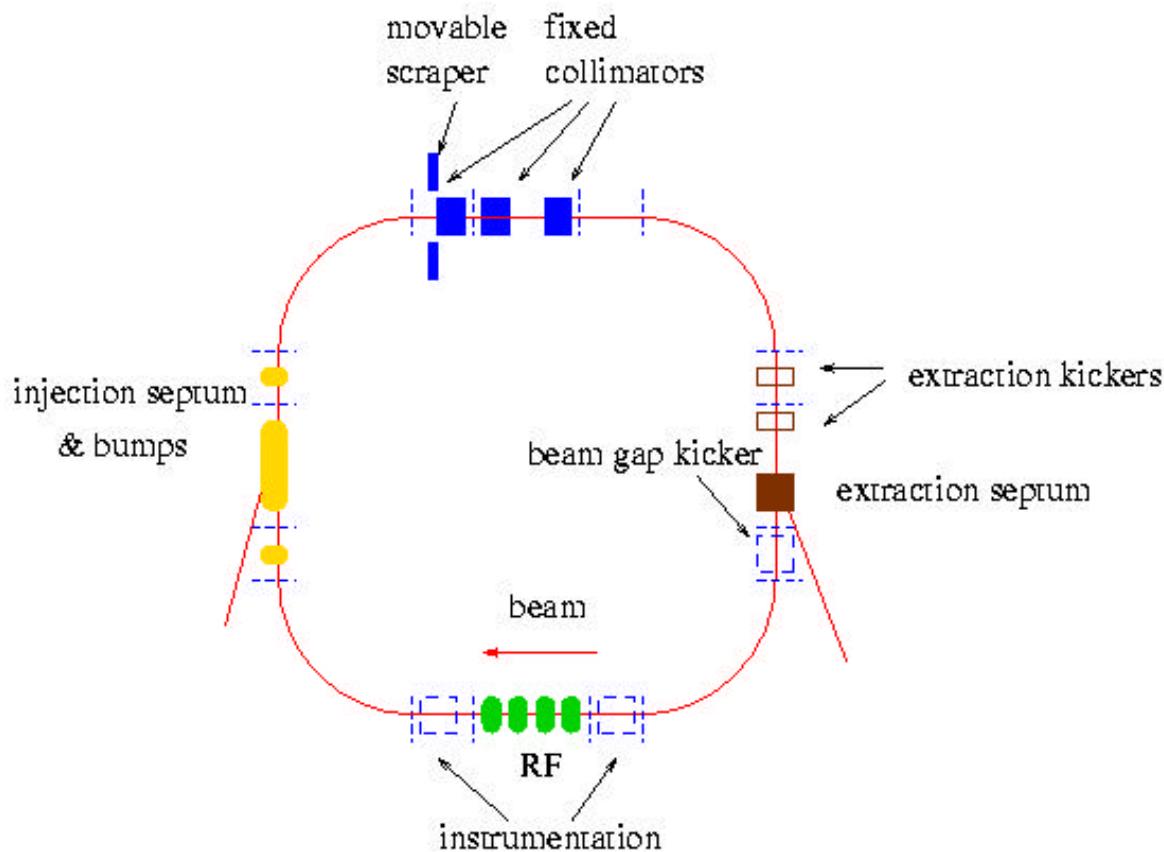
# Spallation Neutron Source



- 60 Hz repetition rate,  $2 \times 10^{14}$  per pulse, 2 MW proton facility
- In its 4th year of a 7-year construction cycle
- H<sup>-</sup> Source, RFQ, DTL, CCL, SRF linac, Accumulator, Hg-target



# Ring: fixed-energy, hybrid lattice



- No energy ramping
- Long straight-section, large aperture
  - Injection flexibility
  - Collimation efficiency
- Four straight-sections for four functions
  - Injection;
  - RF;
  - Collimation;
  - Extraction
  - Diagnostics all-around
- Dispersion-free injection
  - Decoupled H, V, L

# Lattice design-philosophy

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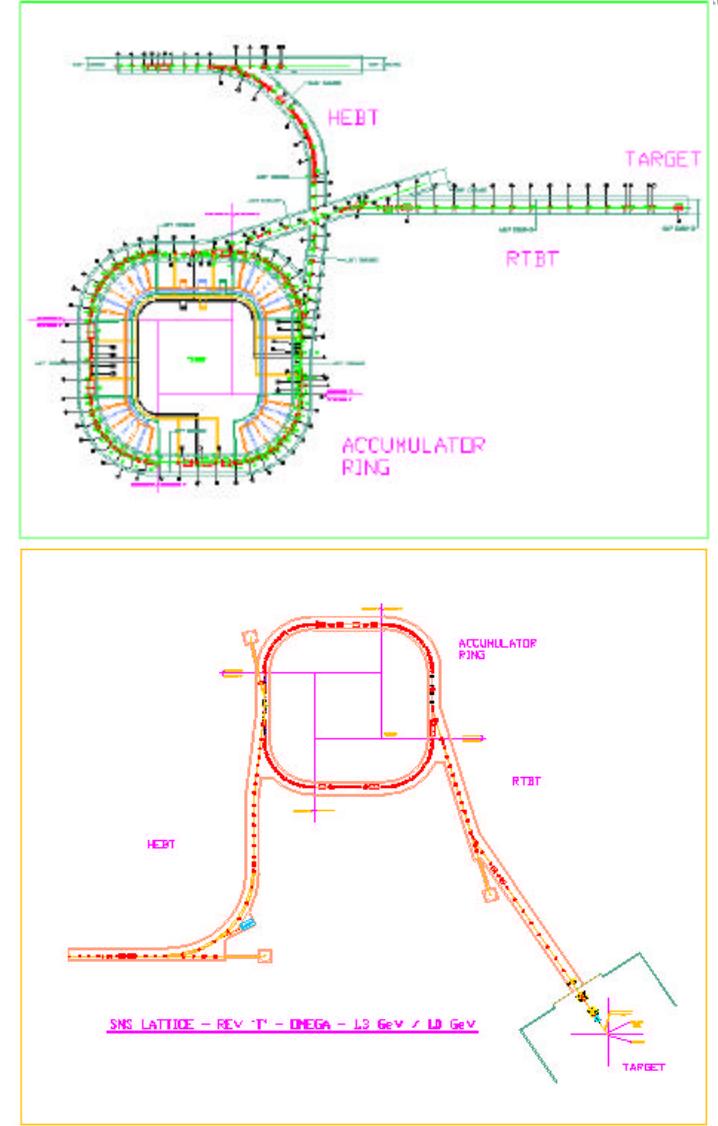


- Separate functions for each straight-section
  - Collimation section expected to be “hot”
  - Injection section needs frequent access (e.g., foil change)
- Compact arc, easy correction
  - FODO cells;  $2\pi$  phase-advance per arc for dispersion suppression
- Long, uninterrupted straight-sections
  - Injection chicane independent of lattice tuning
  - Easy placement collimator, low beam loss on magnets in between
- Large acceptance
  - Matching between arc and straight for a fixed dipole gap height
- Simplicity & flexibility
  - Five families of quadrupoles
  - Large tuning range (H 1 unit, V 2 units), split tune/same tune

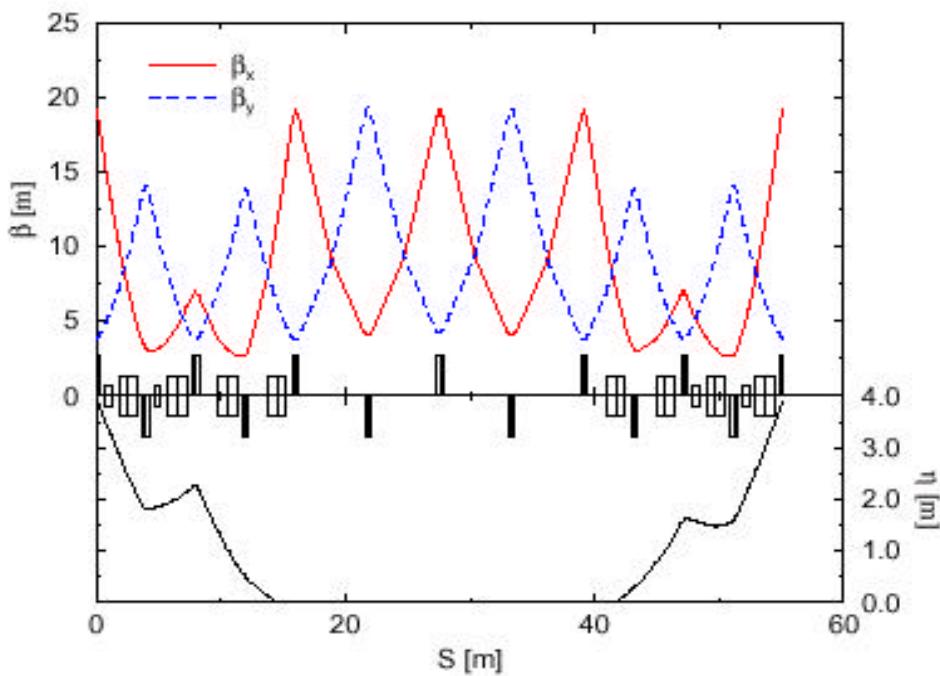
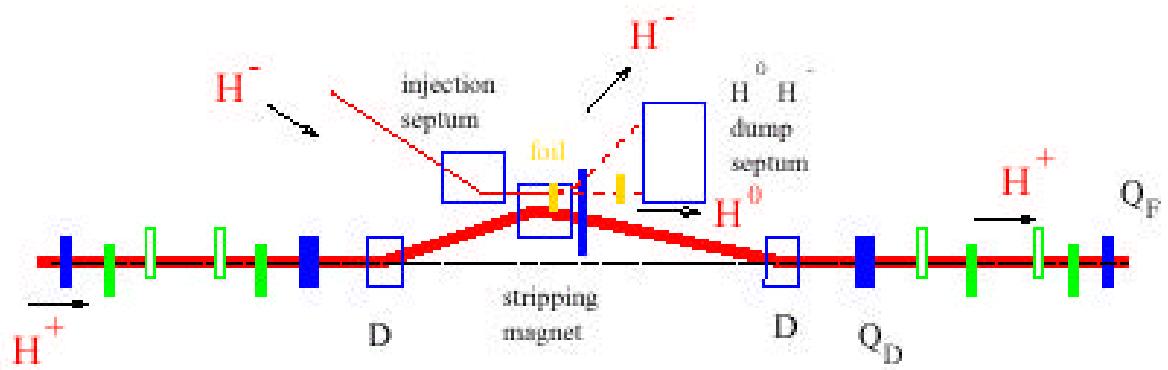
# Ring lattice evolution



- From  $\alpha$  to  $\Omega$  (October 1999):
  - ease maintenance
- From all-FODO to hybrid:
  - 50% increase in acceptance
  - uninterrupted straight length increase: from 5.2 m to 12.5 m
  - collimation efficiency increase: from 80% to 95%
  - injection decoupled from tuning
- Ring size increase (March 2000)
  - from 221 to 248 m circumference
  - improved maintainability
  - lower FE peak current, less foil loss
  - compatible with 1.3 GeV (SC linac)



# SNS Ring old lattice (1999)

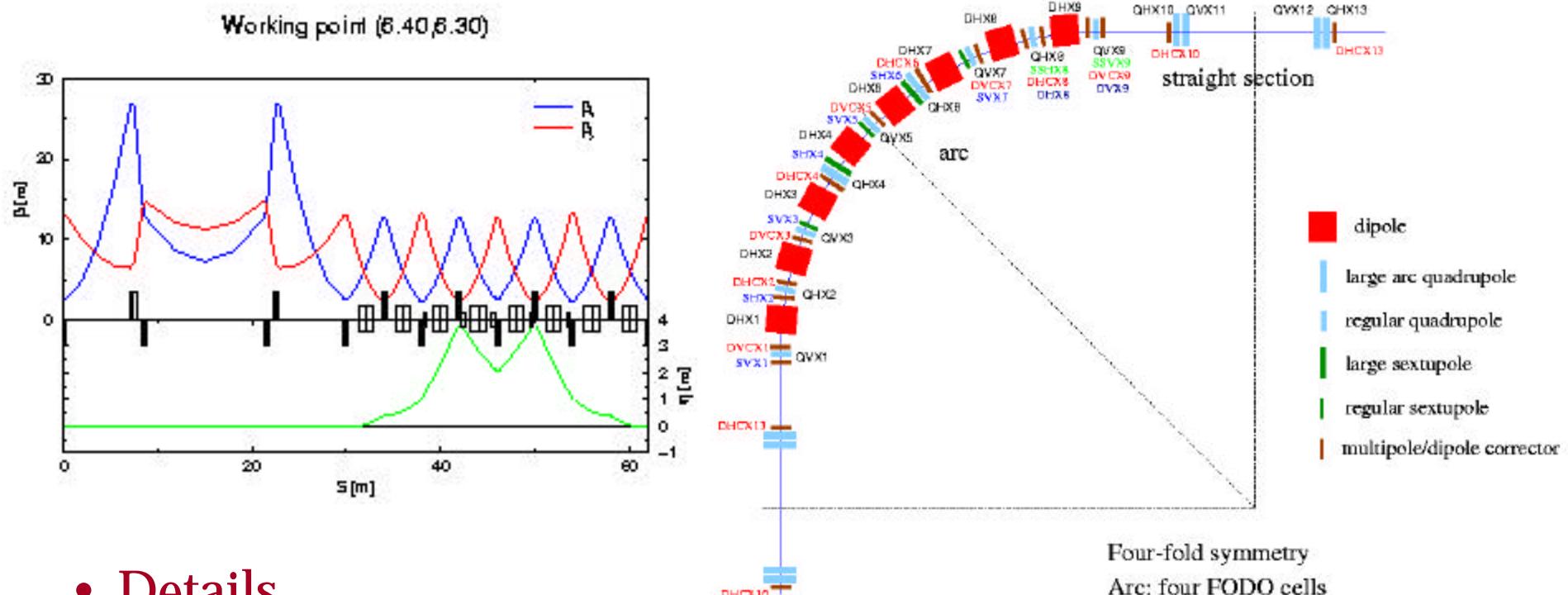


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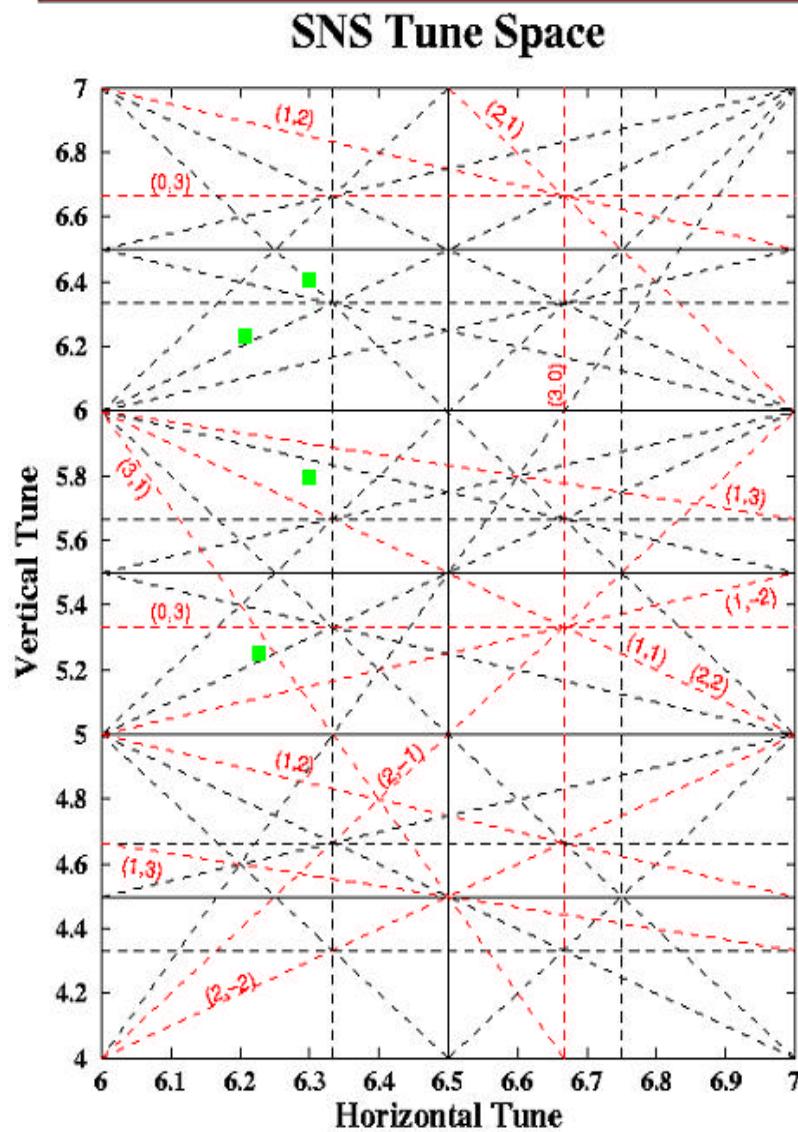
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# Ring lattice (after 2000)



- Details
  - Dipole centered between quads for maximum acceptance
  - Quads sandwiched by correctors
  - Narrow quads in straight section

# SNS tune space



Tunability: 1 unit in horizontal,  
3 units in vertical (2 units due  
to bump/chicane perturbation)

- Structural resonances (up to 4th order)
- All other resonances (up to 3rd order)
- Working points considered
  - (6.30,5.80) - Old
  - (6.23,5.24)
  - (6.23,6.20) - Nominal
  - (6.40,6.30) - Alternative

# Expected Tune-shifts



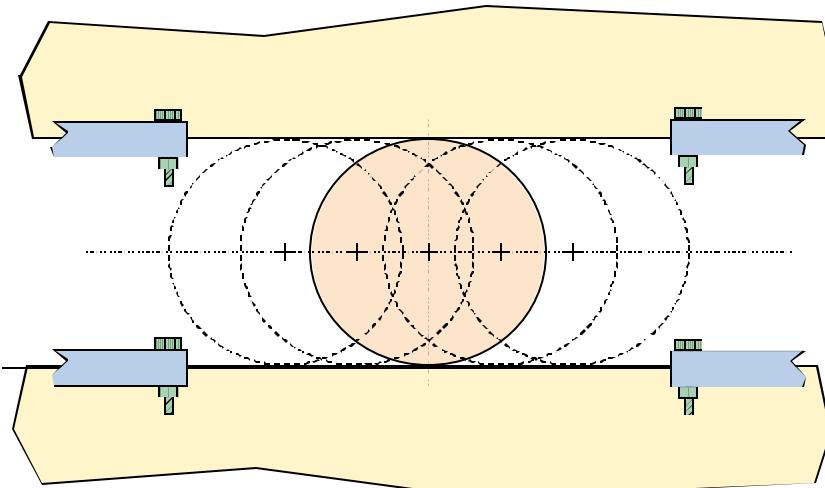
Mechanism	Tune-shifts
Space Charge (2MW beam)	0.15-0.20
Chromaticity ( $\delta p/p = 1\%$ )	$\pm 0.08$
Quadrupole fringe-field	0.025
Uncompensated magnet errors	$\pm 0.02$
Compensated magnet errors	$\pm 0.002$
Chromatic Sextupoles	$\pm 0.002$
Fixed injection chicane	0.004
Injection painting bump	0.001

$480 \pi \text{ mm mrad}$

# Ring dipole field quality

- Findings
  - Good multipole values ( $\sim 10^{-4}$ )
  - Undesirable variation in dipole ITF (up to  $2 \times 10^{-3}$ )
    - » Solid-core iron, heats variation
    - » Mechanical gap variation
- Transfer function retro-fit with shimming

Wanderer, Jain, Jackson, Papaphilippou et al



SNS DIPOLE MEASUREMENTS: FIVE HORIZONTAL POSITIONS; 2 INCHES APART

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## Summary of Field Quality in SD17 Dipoles

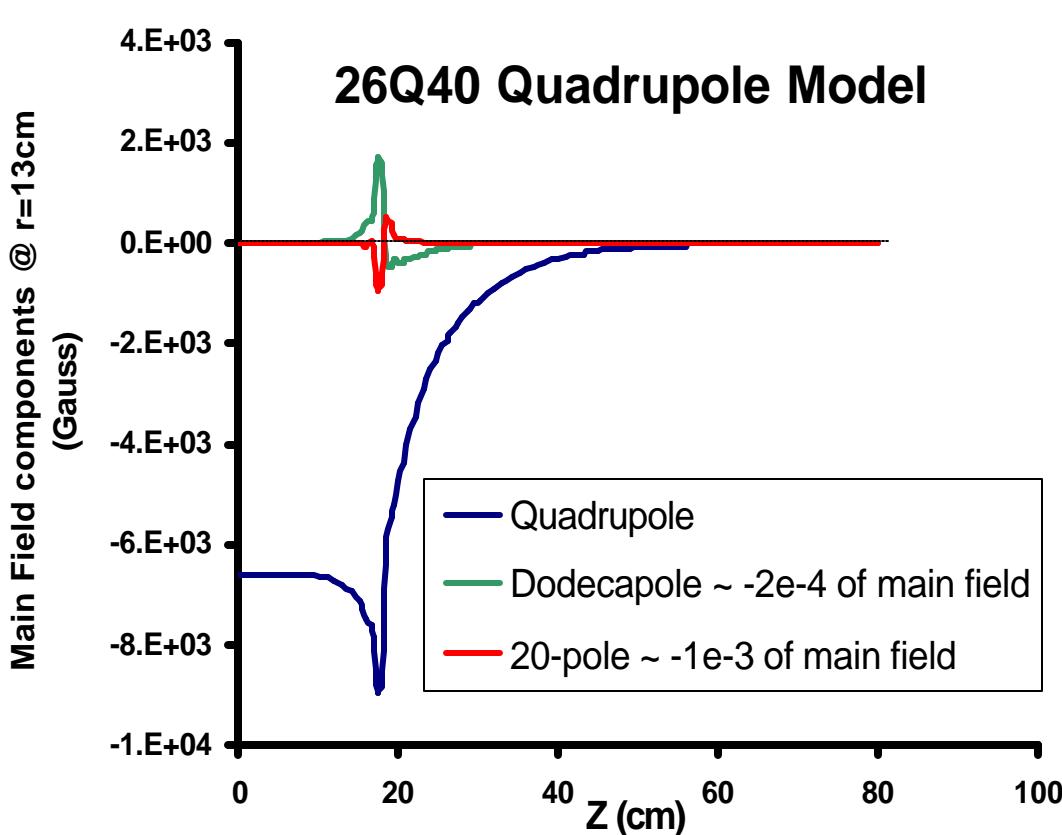
Harmonics in "Units" at a reference radius of 80 mm  
(10 Magnets; Center Position)

Normal Harmonics	1.0 GeV		1.3 GeV		coil angle calibr. drifts
	Mean	Std.Dev.	Mean	Std.Dev.	
I.T.F. (T.m/kA)	0.25241	0.100%	0.24597	0.074%	
Fld Angle (mr)	-0.81	1.06	-0.84	1.06	
$b_0$	10000.0	0.00	10000.0	0.0	
$b_1$	-105.16	0.14	-103.79	0.17	
$b_2$	0.30	0.43	-6.13	0.44	
$b_3$	2.11	0.16	2.54	0.17	
$b_4$	1.15	0.24	-0.45	0.23	
$b_5$	0.06	0.10	0.07	0.10	
$b_6$	-0.32	0.17	-0.51	0.17	
$b_7$	0.15	0.07	0.14	0.07	
$b_8$	-0.06	0.17	-0.05	0.17	
$b_9$	-0.05	0.07	-0.05	0.07	
$b_{10}$	-0.19	0.20	-0.19	0.20	
$b_{11}$	0.01	0.08	0.01	0.08	
$b_{12}$	0.12	0.22	0.12	0.22	
$b_{13}$	0.01	0.06	0.01	0.06	
$b_{14}$	-0.09	0.23	-0.09	0.23	
Sector dipole					

# Quadrupole magnet modeling



W. Meng, N. Tsoupas et al



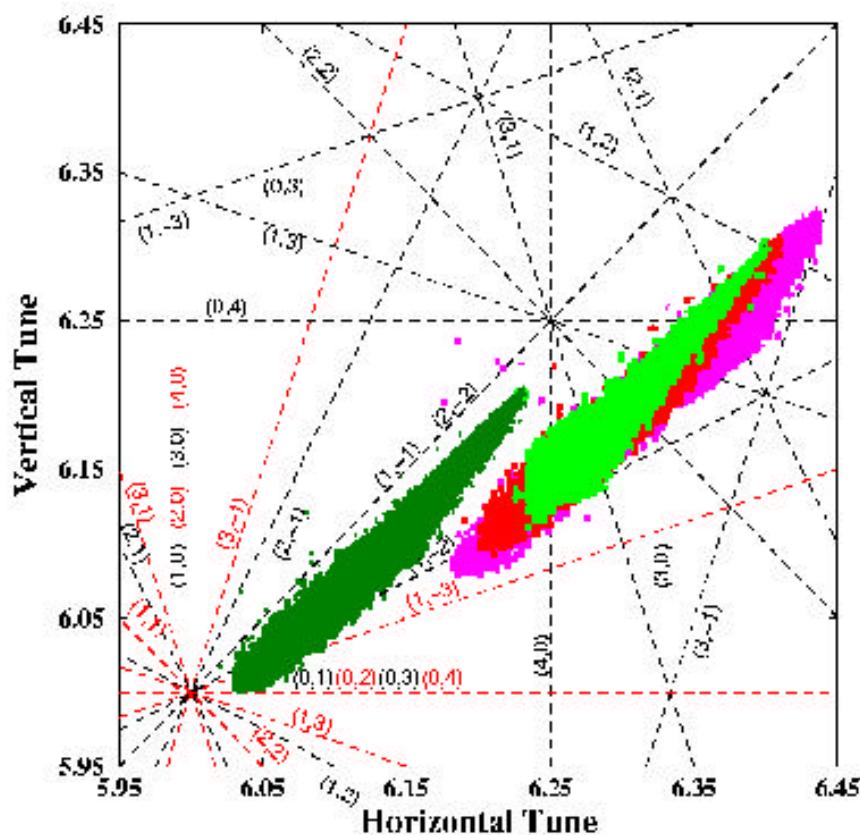
- 3D Tosca model of the wide aperture arc quadrupoles achieved required field quality with optimized edge chamfers (measurement in progress)
- Other quadrupoles modeling is being finalized
- Corrector magnet parameters frozen and modeling in progress
- Fringe-field interference studies between adjacent quads and correctors are under way. Steel to steel distance fixed at 20cm.

# Working Points (6.40,6.30) - (6.23,6.20)



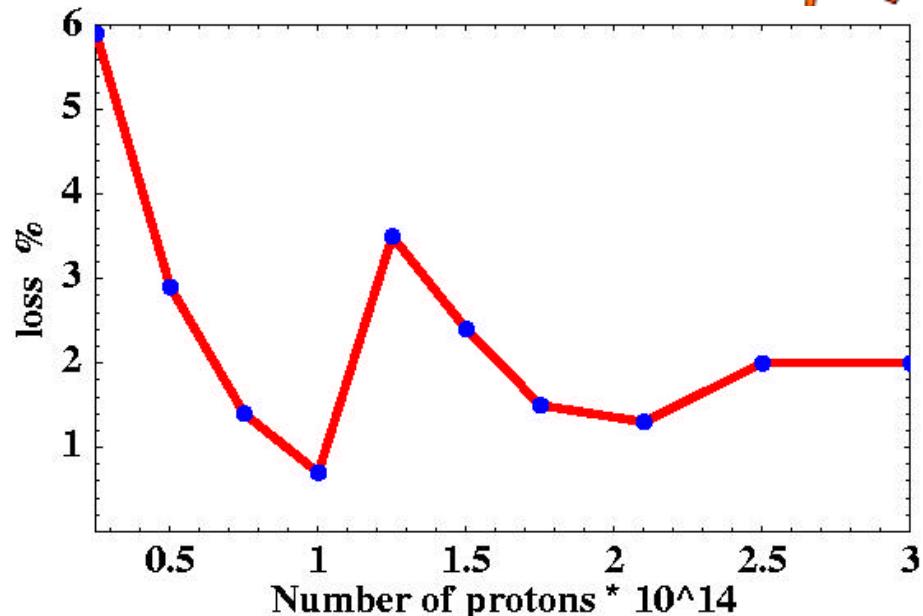
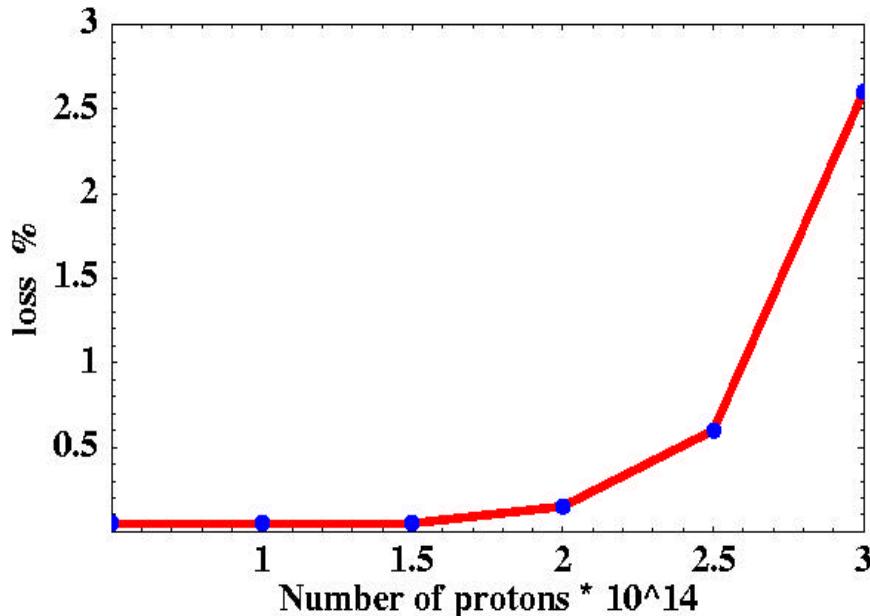
Identification of resonances for new working points

SNS Working Points



N	Resonances	Type	Perturbation	Correction
2	(2,0) (0,2)	Normal quadrupole	Quadrupole errors & misalignment	Quad TRIMS
2	(1,-1)	Skew quadrupole	Magnet Tilt - Space charge	Skew Quad. round beam
3	(3,0) (1,2) (1,-2)	Normal sextupole	Sextupole errors in dipoles	Sextupoles
3	(2,1) (2,-1) (0,3)	Skew sextupole	Magnet skew sextupole error	Skew Sext.
4	(4,0) (2,2) (2,-2) (0,4)	Normal octupole	Quadrupole fringe-fields, space-charge	Octupoles
4	(3,1) (3,-1) (1,3) (1,-3)	Skew octupole	Magnet errors	None

# Resonance-loss model



- **( $Q_x, Q_y$ )=(6.23, 6.20)**
  - free of dangerous resonances
  - losses only in the vicinity of half-integer resonance at high beam intensities.
- **( $Q_x, Q_y$ )=(6.4, 6.3)**
  - strong losses due to the 3<sup>rd</sup> and 4<sup>th</sup> order resonances
  - If resonances corrected good for intensity upgrade.

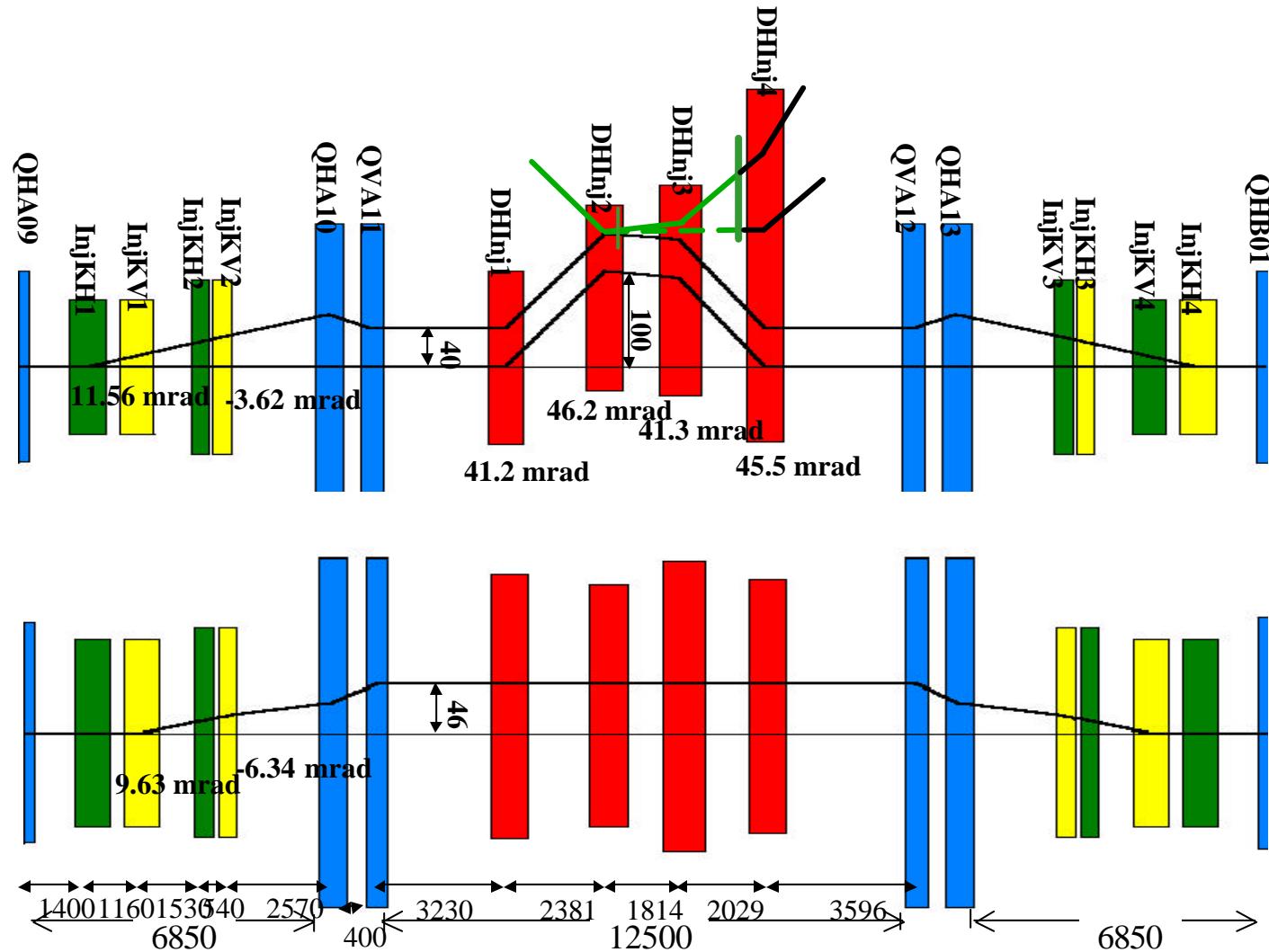
# Ring simulation codes development



N. Malitsky, A. Shishlo (UAL); J. Holmes, V. Danilov, S. Cousineau (ORBIT)

	UAL	ORBIT	FTPOT	MAD 8	MARYLIE 3.0	ACCSIM	SIMPSONS
<b>Interface</b>	PERL API	SuperCode	FTPOT	MAD	MARYLIE	ACCSIM	SIMPSONS
<b>MAD elements</b>	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<b>Errors</b>	Yes	No	Yes	Yes	No	No	Yes
<b>Tracking</b>	Thin lenses	Matrices + nodes	Thin lenses	Lie algebra	Lie algebra	Matrices + nodes	Thin lenses
<b>Mapping</b>	Any order	Second order	Second order	Third order	Third order	Linear order	No
<b>Painting</b>	Yes	Yes	No	No	No	Yes	Yes
<b>Fringe Field</b>	Yes (Maps)	No	No	No	Yes	No	No
<b>Space Charge</b>	3D	3D	No	No	No	2.5D	2D and 3D
<b>Analysis (Twiss ...)</b>	Yes	No	Yes	Yes	Yes	No	No
<b>Optimization (Lattice ...)</b>	No	No	No	Yes	Yes	No	No
<b>Correction (Orbit ...)</b>	Yes	No	Yes	Yes	Some	No	No
<b>Impedance</b>	Yes	Yes	No	No	No	No	No
<b>Collimator</b>	in progress	Yes	No	No	No	Yes	No
<b>Integration of lattices</b>	Yes	No	No	No	No	No	No

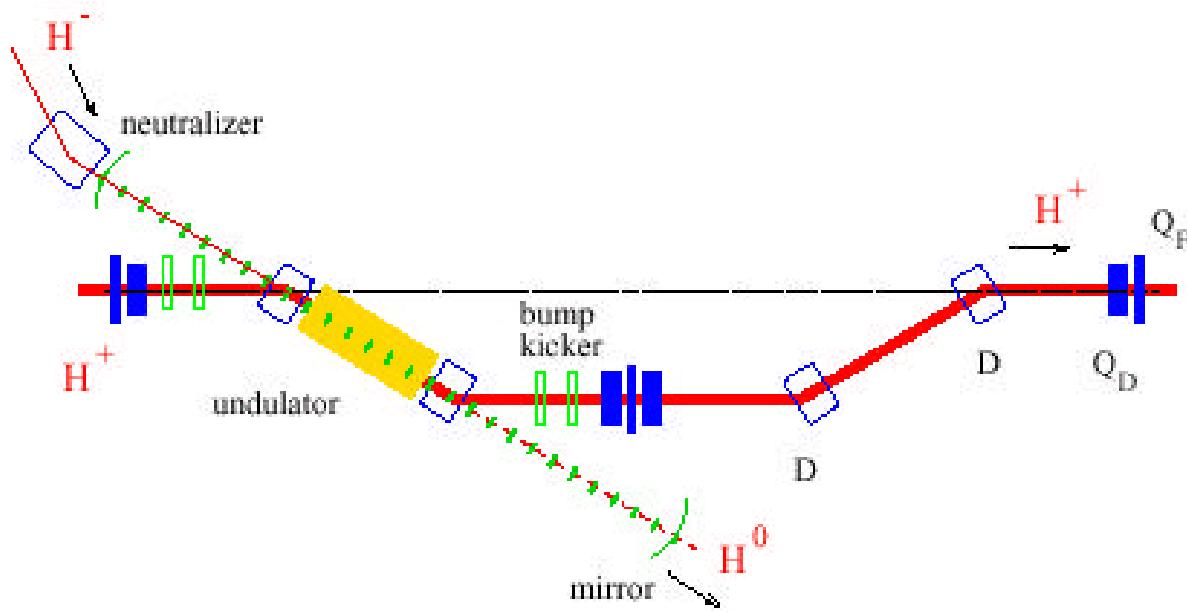
# Injection section layout



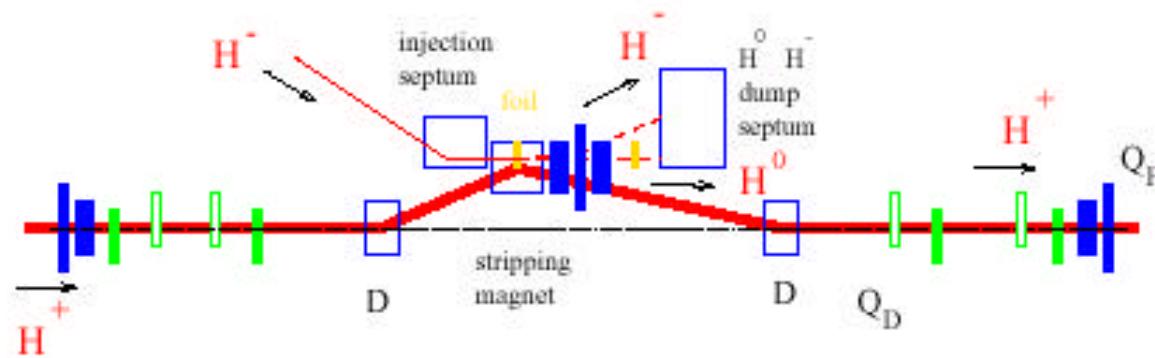
# Lattice for either foil or laser stripping



- 1999 study

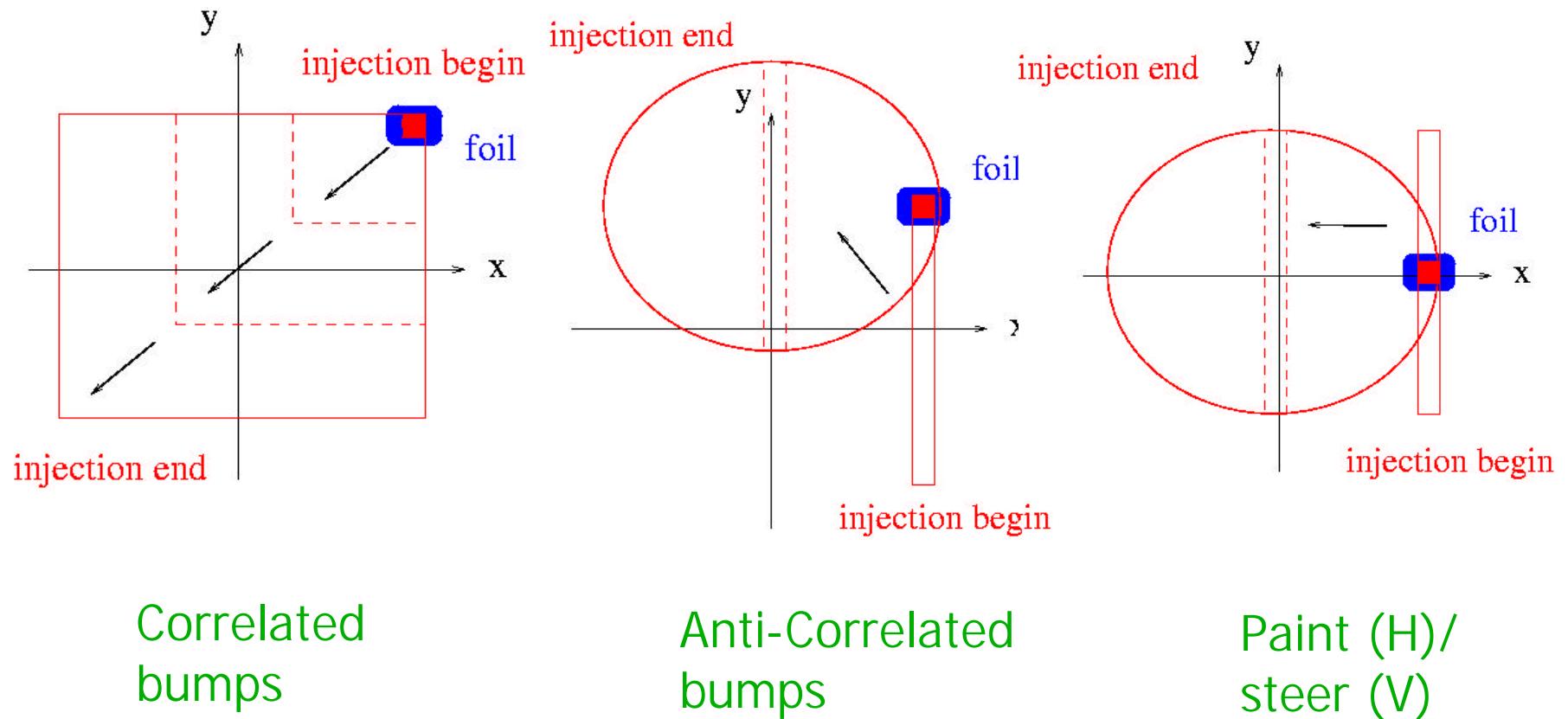


– Laser  
stripping



– Foil  
stripping

# Transverse painting schematic



# Painting scheme comparison



Scheme	Advantage	Disadvantage
<b>Correlated</b>	<b>Paint over halo (square beam profile)</b>	<b>Singular density Coupling emittance growth</b>
<b>Anti-correlated</b>	<b>Ideal uniform distribution Immune to coupling (circular beam profile)</b>	<b>Halo growth due to space charge Extra 50% aperture Extra acceptance needed</b>
<b>Coupled (correlated)</b>	<b>Paint over halo (diamond beam profile)</b>	
<b>Paint (H) / steer (V)</b>	<b>Similar to anti-corr. Paint Less fast kickers</b>	<b>Foil support difficult suscep. to operational error</b>
<b>Paint (V) / steer (H)</b>	<b>Similar to anti-corr. Paint Less fast kickers</b>	<b>Vertical injection suscep. to operational error</b>
<b>Oscillating bump</b>	<b>Uniform distribution Paint over halo</b>	<b>Fast power supply switch Extra 50% aperture (H&amp;V)</b>

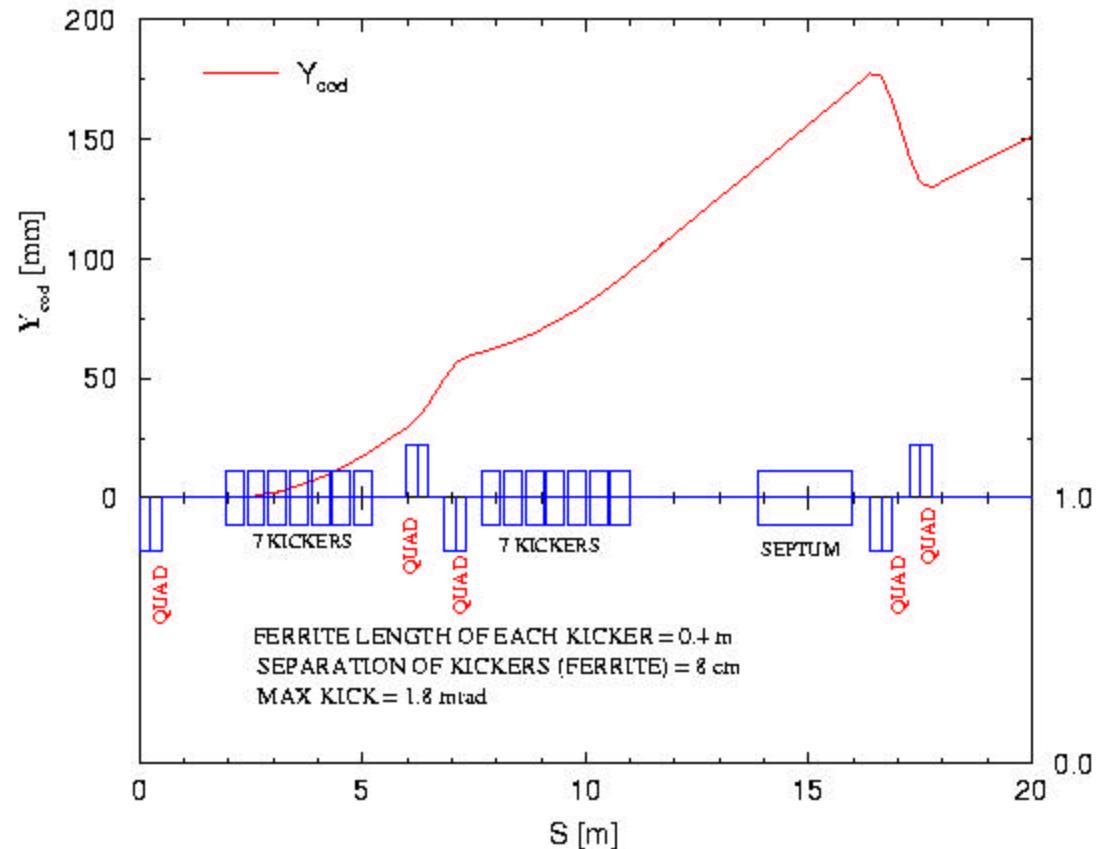
# Extraction layout



- A reversed process of single-turn injection

$$\theta = \frac{x}{\sqrt{\beta_{sep}\beta_{kick}}} \sin \Delta\mu$$

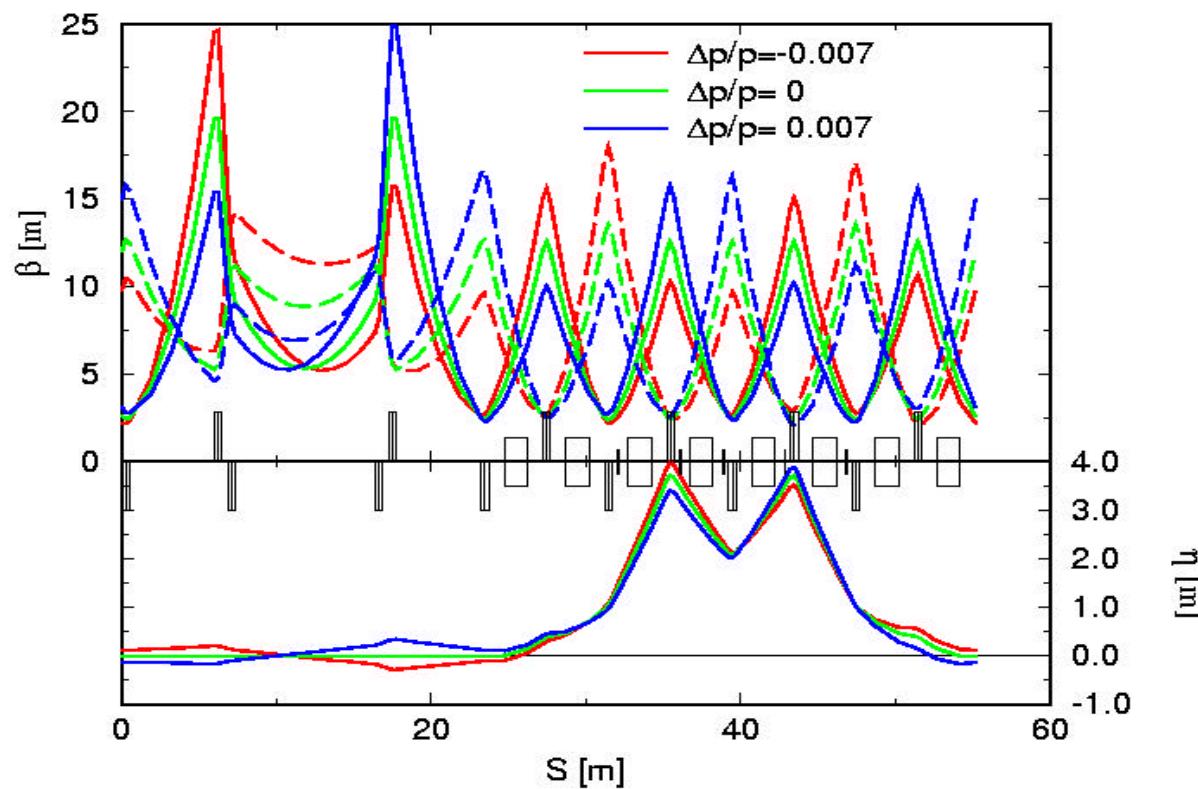
- Example
  - Multiple (14) kickers vertically deflect beam
  - Horizontal bending beam away with a septum (e.g. Lambertson dipole)
  - Single-turn, no pre-bumps
  - Zero-loss for 1 kicker failure



# Chromatic adjustment



Limitation of a 2-family sext. system



- Preserve lattice symmetry:
  - Avoid resonance
- Multi-family sextupole:
  - Compensate optics
  - Preserve dynamic aperture
  - Full-range chromatic control

# Correction packages



Baseline	Quantity	Powering	Justification
Dipole	52 (+2)	Individual	Injection dump dipoles
TRIM Quadrupoles	52	28 families	Beta beating correction due to lattice symmetry breaking
Skew Quadrupoles	16	Individual	Coupling correction
High-Field Sextupoles	20	4 families	Correction of large chromatic effect
Normal Sextupoles	8	Individual	Sextupole resonance correction due to sextupole errors and octupole feed-down
Skew Sextupoles	16	8 families	Skew sextupole resonance correction (AGS booster)
Octupoles	8	Individual	Octupole resonance correction due to quadrupole fringe-fields

# Resonance identification for (6.3,5.8)



Work. Point	dp/p (%)	Resonances	Possible Cause	Correction
(6.3,5.8)	-2.0	(2,-1)	a3 random error	Mag. Qual. + Skew Sext.
	-1.5	(3,3)	b6 error on quads	Mag. Qual.
	-1.0	(3,1) (1,3)	a4 random error	Mag. Qual.
	-0.5	(3,0) (1,2)	b3 error + dipole fringe fields	Mag.Qual. + Sextupole
	0.0			
	0.5			
	1.0	(1,1) (2,2)	Quad. fringe fields	Skew Quad. - Octupole
		(4,0) (2,-2) (0,4)	Quad. fringe fields	Octupole
		(3,-1) (1,-3)	a4 random error	Mag. Qual.
	1.5	(1,1) (2,2)	Quad. fringe fields	Skew Quad. - Octupole
		(4,0) (2,-2) (0,4)	Quad. fringe fields	Octupole
		(1,-3)	a4 random error	Mag. Qual.
	2.0			

# Summary

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- Lattice is key to a low-loss performance
  - Long, uninterrupted straight section
  - Large acceptance (matching)
- Separated functionality at periodicity 4
  - Compact arc for bending & correction
  - Dispersion-free injection
  - Separated sections for injection and collimation for easy maintenance
- Present hybrid-lattice is a good choice for an accumulator